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MESO-SCALE DISTRIBUTION OF SUMMER MONSOON RAINFALL NEAR THE WESTERN GHATS (INDIA)

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ABSTRACT

The spatial distribution of southwest monsoon rainfall is studied over Maharashtra State (India), which includes part of the well-known Western Ghats mountain range, near its western boundary, running almost from north to south, perpendicular to the summer monsoon current in the lower troposphere. Meso-scale analysis of daily rainfall is performed for Maharashtra State, including the Western Ghats, for the two mid-monsoon months of July and August, during the 10-year period of 1971–1980. Strong and weak monsoon days were identified for the 5-year period of 1976–1980. The meso-scale pattern of average daily rainfall is obtained separately for strong and for weak monsoon conditions.

All these average patterns show the following features: (i) the rainfall increases rapidly from the Arabian Sea coast close to the line of maximum height of the Western Ghats; (ii) there are two rainfall maxima corresponding to the two mountain peaks parallel to the coast line; (iii) between the two mountain peaks, there is a valley which is narrow at the western end (upwind end), broadening towards the east (on the downwind side). Ground contour height of the valley rises eastwards and ends as a part of the Deccan Plateau east of the Ghats. Here the valley opens out like a funnel with higher mountains flanking its two sides. In the valley, the rainfall increases from the coast up to the line of maximum height of the Ghats, and then decreases eastwards towards the plateau. The rainfall isopleths also take a funnel-shaped configuration. An interesting feature is that near the wider section of the valley funnel, there is a rainfall minimum and then the rainfall increases further eastwards on the downwind side. This feature of rainfall minimum is somewhat similar to the rainfall minimum reported by Asnani and Kinuthia (personal communication); Asnani (Asnani GC. 1993. *Tropical Meteorology*, Vol. I. Prof. G.C. Asnani: Pune, India; 603) attributed the rainfall minimum to the Bernoulli effect. A somewhat similar phenomenon is assumed in the present study area.

KEY WORDS: Western Ghats; orography; meso-scale rainfall; Bernoulli effect

1. INTRODUCTION

In a mountainous region, where orography is irregular, rainfall features are also irregular and complex, with respect to time and space. During time-averaged rainfall, the irregularities pertaining to time become evened out. If the spatial distribution of time-averaged rainfall is examined, it is expected that it will reveal a pattern that would have a relationship with permanent (time-constant) features of orography. According to Mooley (1978), the Western Ghats appear to play a differential role and contribute to the observed major discontinuities in the monsoon activity. The Western Ghats enhance (decrease) rainfall activity substantially under favourable (unfavourable) conditions.

In the present study, a computer-smoothed spatial configuration of time-averaged rainfall of what is termed a meso-scale network of observatories is produced. A correspondence between the configuration of time-averaged rainfall isopleths and the time-invariant orography is expected. The comparison between the rainfall and altitude configurations should reveal some dynamical relationship between rainfall and orography.

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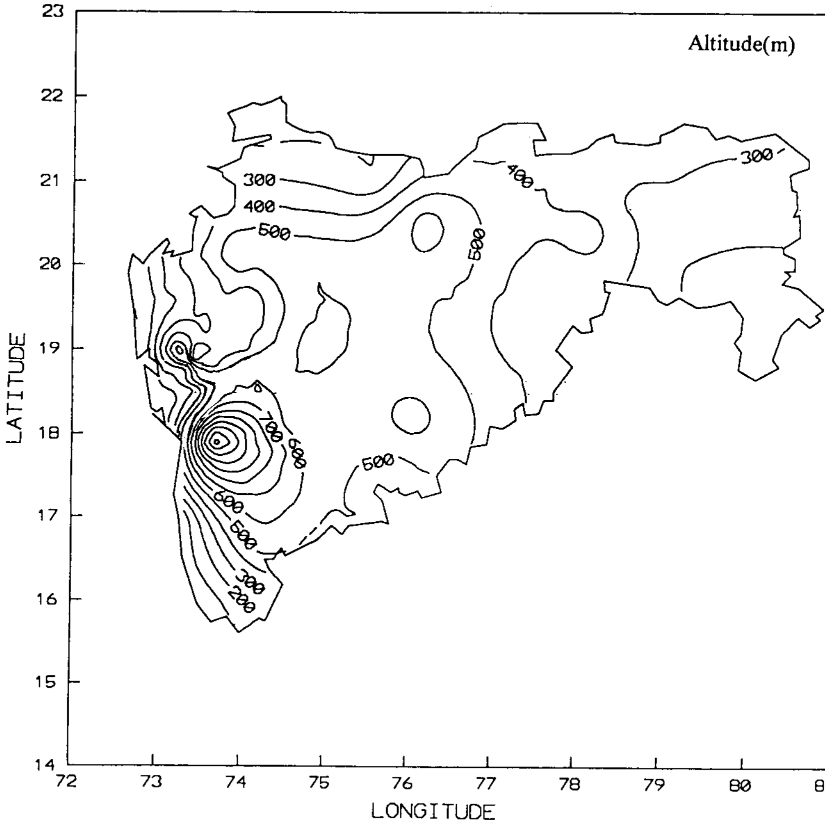

Figure 1. Orographic features of Maharashtra State

Table I. Stations in Maharashtra State in India which are used in the analysis

Serial number	Station name	Altitude (m)	Serial number	Station name	Altitude (m)
1	Dahanu	005	26	Nasik	598
2	Podar M.	010	27	Ahmednagar	657
3	Santacruz	014	28	Jeur	521
4	Colaba	011	29	Aurangabad	581
5	Alibag	007	30	Chikhalthana	579
6	Harnai	020	31	Jalgaon	201
7	Ratnagiri	035	32	Bhir	519
8	Devgad	036	33	Sholapur	479
9	Vengurla	009	34	Osmanabad	655
10	Matheran	756	35	Buldhana	650
11	Bhivpuri	136	36	Parbhani	423
12	Khopoli	094	37	Nanded	358
13	Lonavala	625	38	Pusad	334
14	Khandala	539	39	Akola	282
15	Bhira	096	40	Akola (Aero)	309
16	Mahabaleshwar	1382	41	Amraoti	370
17	Ozar	608	42	Yeotmal	451
18	Lohogaon Indian Air Force	593	43	Wardha	283
19	Poona	559	44	Nagpur (Aero)	310
20	Wanorie Armed Forces Medical College	594	45	Nagpur Meyo Hospital	311
21	Kolhapur	570	46	Chandrapur	193
22	Nandurbar	206	47	Sironcha	123
23	Malegaon	437	48	Brahmapuri	229
24	Baramati	551	49	Gondia	313
25	Sangli	549			

It is broadly known that the rainfall increases on the windward side of a mountain range and decreases after crossing the line of its maximum height. Sarker (1967) has pointed out that the maximum rainfall on the windward side of the Western Ghats occurs not at the line of maximum height, but 5–10 km ahead of the maximum height. He adopted a smooth profile of orography, starting from sea level around 60 km ahead of the crest height of the mountain which was approximately 1 km above mean sea level (MSL). On the leeward side of the mountain peak, the terrain was represented in the form of a plateau and he used a linear form of the mountain wave equation. The ground profile was represented as the sum of Fourier waves in the x-direction. Sarker (1967) obtained lee wave solutions with a horizontal wavelength between 19 and 32 km for the five cases that he analysed. One particular case, that of the 5 July 1961, which he studied and presented in detail, had a horizontal wavelength of 19 km. Sarker's model gave maximum rainfall about 10 km ahead (on the upwind side) of the mountain crest.

The authors have attempted to obtain the meso-scale structure of mean July and mean August rainfall pattern in Maharashtra State, with particular emphasis on the structure of the rainfall pattern along the Western Ghats between 18°N and 21°N, which lie near the western boundary of Maharashtra State.

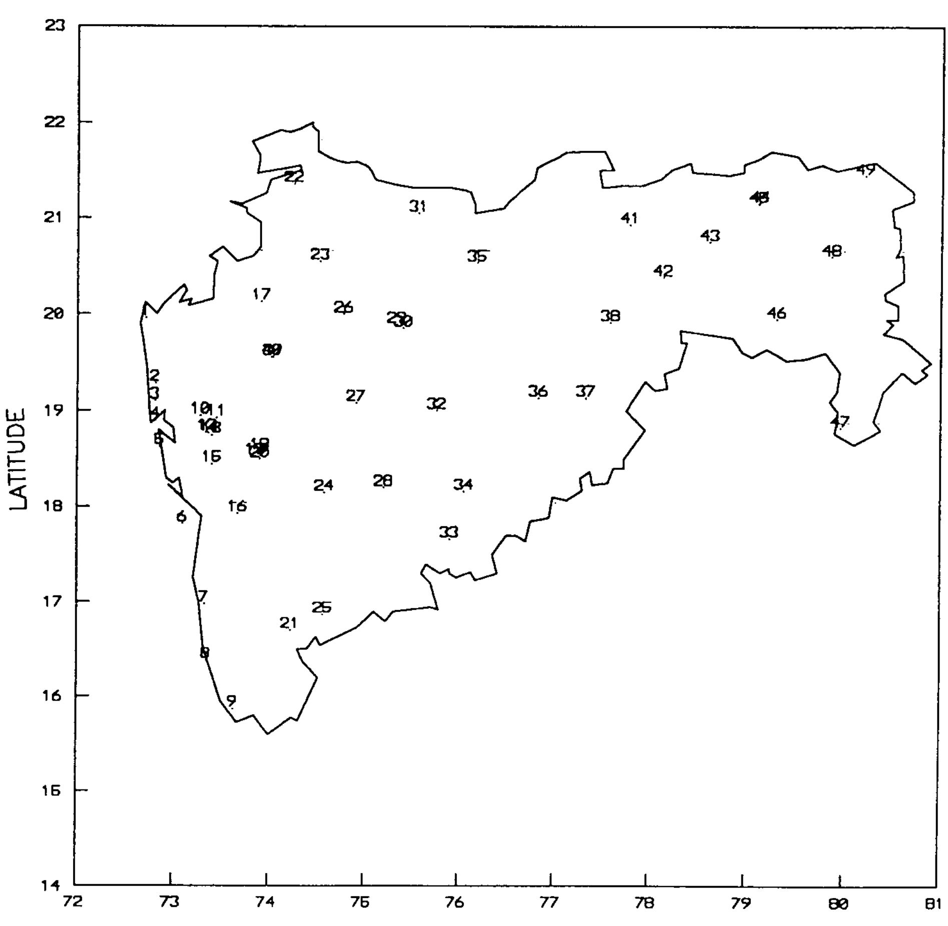

Figure 2. Locations of the stations used in the analysis, numbers are the same as the serial numbers in Table I

2. DATA AND ANALYSIS

Figure 1 gives the orography of Maharashtra State. The area contains 49 observatories with daily rainfall data for many years, of which the ten-year period of 1970–1980 was selected. The elevation values for the same 49 observatories were obtained, as shown in Table I. The elevation values were obtained from the catchment book published by the India Meteorological Department. Their distribution is shown in Figure 2. The orographic pattern obtained from these elevation data is shown in Figure 1.

It is evident that between the two high mountain peaks, Matheran (18°59′N, 73°17′E) and Mahabaleshwar (17°56′N, 73°40′E), there is a valley rising eastwards from sea level to 500 m, as part of the Deccan Plateau east of the Ghats. Here the valley opens out like a funnel, with higher mountains on its two sides.

Average daily rainfall for July for the years of 1971–1980 is shown in Figure 3. The rainfall pattern for the month of August is similar to the pattern for July. It is evident that the daily rainfall isopleths closely follow the ground contour values of the Western Ghats. The following additional features are noteworthy:

(i) The line of maximum rainfall almost coincides with the line of highest orography. With the present distribution of rain-gauge stations, it is not possible to make a finer distinction and state whether the rainfall maximum is 5–10 km ahead (upwind) of the line of highest orography.
(ii) On the downwind side of the line of highest orography, there is a dip in the rainfall isopleths in the direction of the valley, showing that the rainfall is higher to the north and to the south of it, being qualitatively minimal here.
(iii) The most important feature of the rainfall isopleths is the rainfall minimum on the leeward side of the mountain along the central line of the funnel-shaped valley. The question then arises as to why

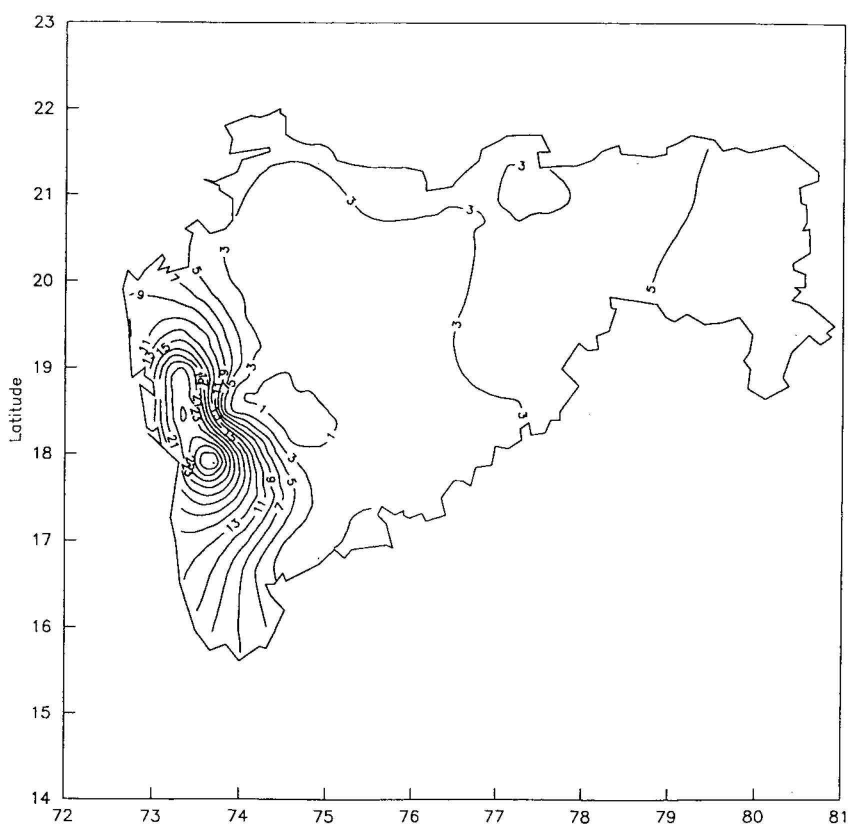

Figure 3. Average daily rainfall (mm) for July, for the period 1971–1980

there is a rainfall minimum near the funnel-shaped opening of the valley. In the July pattern, in Figure 3, there is a clear rainfall minimum. Similar rainfall minima, somewhat less than the July minimum, are also observed in the August pattern, to the east of the funnel-like opening of the valley.

(iv) With the help of Indian Daily Weather Reports, strong/weak monsoon days during the months of July and August in the 5-year period of 1976–1980 were identified, and composite rainfall patterns for strong monsoon days were prepared, with separate ones for weak monsoon days. These composite patterns are shown in Figure 4(a) and (b). The patterns of the rainfall minimum on the leeward side of the mountain, along the central line of the funnel-shaped valley seen in Figure 3, are seen more prominently in Figure 4(a) and also in Figure 4(b).

(v) In Figures 3 and 4(a) and (b), rainfall increases slowly towards the east. This further confirms that the funnel-type valley effect extends up to a good distance from the valley, although in a less marked manner than near the end of the valley itself.

3. DISCUSSION

On the windward side of the Western Ghats, the increase of rainfall towards the mountain peak falls in the classical textbook pattern. It is not possible to confirm nor to refute the conclusion of Sarker (1967), that the rainfall maximum occurs a few kilometres upwind of the line of the maximum topographic elevation. The minimum of rainfall downwind of the funnel-shaped end of the valley has not yet been

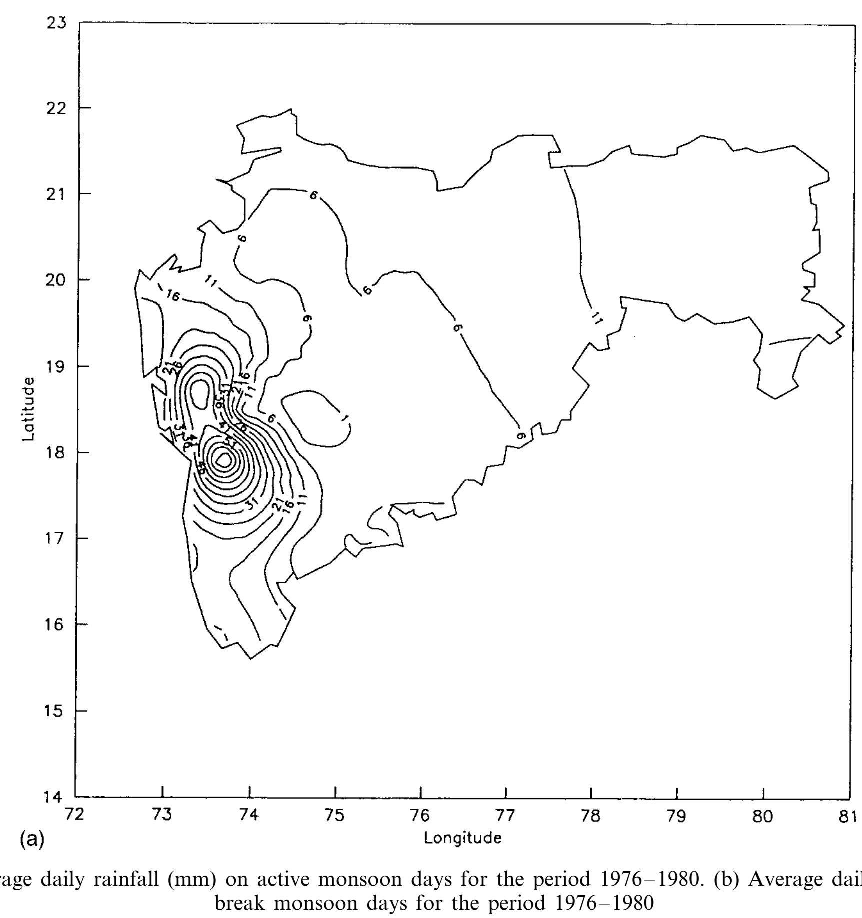

Figure 4. (a) Average daily rainfall (mm) on active monsoon days for the period 1976–1980. (b) Average daily rainfall (mm) on break monsoon days for the period 1976–1980

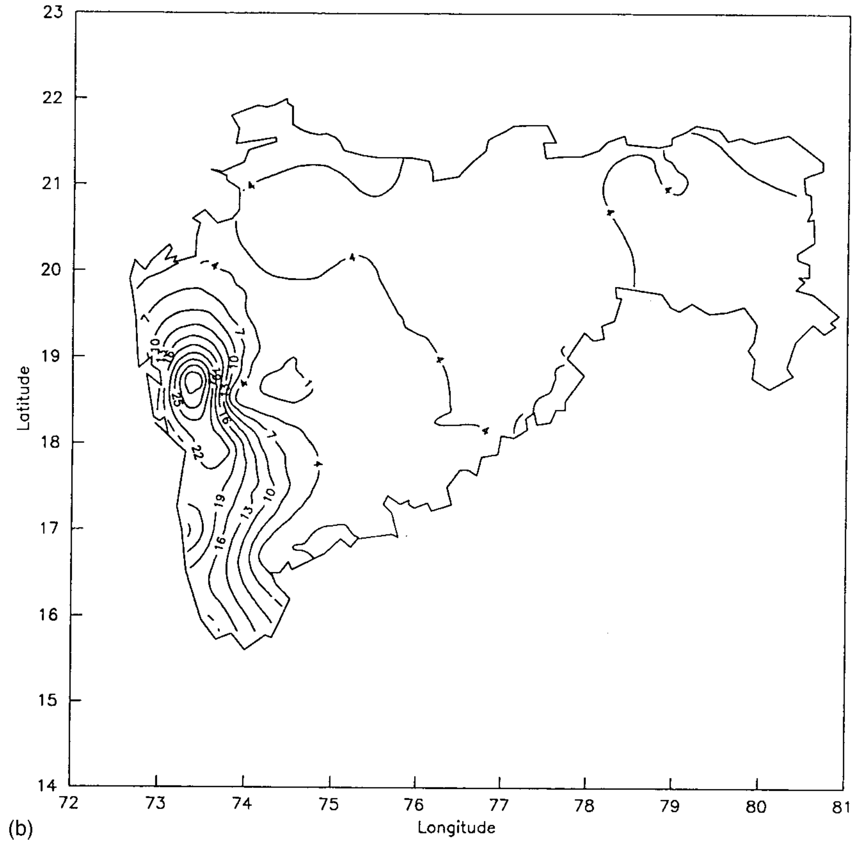

Figure 4 (*Continued*)

highlighted in meteorological literature. Asnani and Kinuthia (personal communication) and Asnani (1993) have found a similar rainfall minimum in the case of the Lake Turkana channel in Kenya, and also in the case of the Palghat Gap on the Indian peninsula in the Western Ghats (10°N). They have attributed it to the Bernoulli Effect. In simple language, under simplified assumptions, Bernoulli's theorem may be stated as follows: under steady-state conditions, a fluid mass flowing horizontally conserves the sum of its potential and kinetic energy. When the boundary conditions constrain the fluid to pass from a narrow cross-section to a wider cross-section, then its velocity decreases, kinetic energy decreases and potential energy in the form of pressure increases; this increase of pressure is called dynamic pressure.

In the case of air flow through funnel-shaped mountain range, Bernoulli's dynamic pressure will be generated on the windward side (wider cross-section). This high pressure region creates subsidence in the layer below. This subsidence causes evaporation of clouds and a decrease of rainfall on the downwind side of the flow. Owino (1997) has carried out a numerical simulation of the Bernoulli Effect and confirmed that there is considerable subsidence near the funnel-type opening on the windward side.

This is a very interesting meso-scale phenomenon which deserves to be highlighted in meteorological literature. The authors are sure that detailed rainfall analysis at the funnel-type opening of mountain gaps and valleys elsewhere in the world will also reveal this interesting feature of the atmosphere.

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